

SIMULATION STUDIES OF A XUV/SOFT X-RAY HARMONIC-CASCADE FEL FOR THE PROPOSED LBNL RECIRCULATING LINCAC *

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Abstract

Presently there is significant interest at LBNL in designing and building a facility for ultrafast (i.e. femtosecond time scale) x-ray science based upon a superconducting, recirculating RF linac (see [1] for more details). In addition to producing synchrotron radiation pulses in the 1-15 keV energy range, we are also considering adding one or more free-electron laser (FEL) beamlines using a harmonic cascade approach to produce coherent XUV & soft X-ray emission beginning with a strong input seed at ~ 200 nm wavelength obtained from a “conventional” laser. Each cascade is composed of a radiator together with a modulator section, separated by a magnetic chicane. The chicane temporally delays the electron beam pulse in order that a “virgin” pulse region (with undegraded energy spread) be brought into synchronism with the radiation pulse, which together then undergo FEL action in the modulator. We present various results obtained with the GINGER simulation code examining final output sensitivity to initial electron beam parameters. We also discuss the effects of external laser noise and shot noise upon this particular cascade approach which can limit the final output coherence.

INTRODUCTION

In the past decade, there has been an increasingly strong interest in developing intense sources of tunable, coherent radiation at extreme ultraviolet and soft x-ray wavelengths. While much of this effort has been concentrated on free-electron lasers (FELs) based upon the principle of self-amplified spontaneous emission (SASE), there is an alternative “harmonic cascade” FEL approach [2][3] which begins with a temporally and transversely coherent input signal from a “conventional” laser in the ultraviolet region (e.g. $\lambda_{in} \sim 240$ nm). This input is then effectively frequency-upshifted via resonant electron-radiation interaction in a series of FEL undulators to produce a short wavelength (e.g. $\lambda_f \sim 4$ nm) final signal with excellent transverse and temporal coherence. This approach relies upon the higher harmonic longitudinal microbunching which naturally accompanies strong microbunching at the fundamental wavelength of FEL resonance $\lambda_s = \lambda_w \times (1 + a_w^2)/2\gamma^2$. Here λ_w is the undulator wavelength, γ is the electron beam Lorentz factor, and a_w is the normalized RMS undulator strength parameter.

Recently, Yu *et al.* [4] have reported successful results from a one stage, High Gain Harmonic Generation (HGHG) experiment at BNL in which a seed laser was used

to produce strong microbunching modulation at 800 nm followed by both strong coherent emission and accompanying FEL gain to saturation at the third harmonic wavelength of 266 nm. At LBNL we are interested in augmenting the proposed LUX (Linac-based Ultrafast X-ray) facility by a multi-stage, harmonic cascade FEL which would operate from UV to soft x-ray (i.e. 1.2 keV) photon energies. Each cascade stage would consist of a “modulator” undulator plus achromatic bend/dispersive section, which strongly microbunches a short portion (e.g. 200 fs) of the electron beam, followed by a “radiator” undulator whose resonant wavelength is tuned to an integral harmonic of the preceding modulator resonance.

By exploiting the ps- or better timing synchronization possible with the recirculating linac configuration of LUX, we will adapt the “fresh beam” idea of Ben-Zvi *et al.* [5] by placing a delay chicane following each radiator undulator. This ensures that a “virgin” e-beam section, lying closer to the pulse head with electrons whose instantaneous energy spread has not been increased by FEL interaction in the upstream modulators, will be brought into temporal synchronism with the radiation pulse. Importantly, both this delay and the use of high radiation power in the modulators (a GW-class seed laser for the first and 100+ MW-class coherent spontaneous emission (CSE) for the subsequent modulators) produces sufficient microbunching in the low gain regime, thus permitting quite short undulator lengths (typically $\leq 1.5L_{gain}$). This design philosophy [6] is different from that studied by Saldin *et al.* [7] who had to limit the amount of induced energy spread in each modulator which thus required the use of high gain radiators. High input power to each modulator also helps alleviate the problem of noise growth accumulating from stage to stage which otherwise can degrade the output longitudinal coherence at short wavelengths.

BASIC CASCADE PERFORMANCE

Here we describe a present design of a FEL harmonic cascade system for LUX. We use reasonably conservative electron beam parameters: 2.5 GeV energy with a uniform $\sigma_E = \pm 200$ keV, 500 A current (1 nC in 2 ps), and 2π mm-mrad normalized emittance. The external laser seed has 1 GW power and is presumed to be fully tunable over the wavelength range 190 – 250 nm. Using time-steady (i.e. monochromatic) simulations with the GINGER code [8], we designed and partially optimized a 4-stage harmonic cascade reaching from 240-nm down to 1-nm wavelength. The undulator and dispersive section parameters are displayed in Table I. The FEL parameter ρ strongly decreases after the 48-nm stage while the effective nor-

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Table 1. Undulator Parameters for a Sample 4-Stage Harmonic Cascade for LUX

λ_s (nm)	λ_w (mm)	a_w	B_w (T)	FEL ρ	L_w (m)		τ_{slip} (fs)		P_{out} (MW)		$\langle b_1 \rangle$		R_{56} (μm)
					rad.	mod.	rad.	mod.	rad.	mod.	rad.	mod.	
240	120	9.69	1.22	2.3×10^{-3}	—	3.6	—	24.0	—	1000	—	0.21	11.3
48	75	5.43	1.10	2.4×10^{-3}	4.0	6.0	8.5	12.8	345	395	0.36	0.22	4.9
12	40	3.65	1.38	1.2×10^{-3}	6.0	5.0	6.0	5.0	113	121	0.16	0.19	2.8
4	30	2.32	1.17	7.6×10^{-4}	5.0	4.0	2.2	1.8	139	142	0.27	0.18	0.4
1	25	0.96	0.58	4.1×10^{-4}	8.0	—	1.1	—	11	—	0.07	—	—

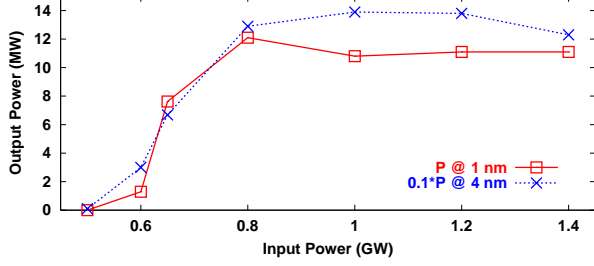


Figure 1: Sensitivity of output power from 4-nm and 1-nm radiator stages to external laser input power at 240 nm.

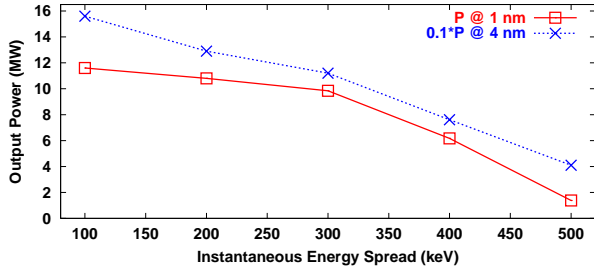


Figure 2: Output power sensitivity to energy spread.

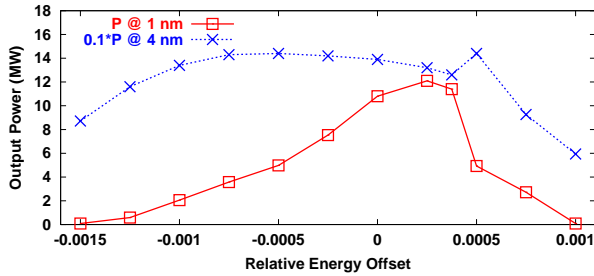


Figure 3: Output power sensitivity to energy offset.

malized energy spread corresponding to transverse emittance increases from 7.5×10^{-5} in the 48-nm radiator to 7.5×10^{-4} in the 1-nm radiator. This last increase strongly exceeds ρ with the consequence of reduced radiation emission due to longitudinal debunching.

The two columns listed under $\langle b_1 \rangle$ refer to the average/output microbunching parameter at the fundamental wavelength for each radiator/modulator, respectively. Our basic philosophy was to make each modulator sufficiently long that $\langle b_1 \rangle$ approached 0.2 at which point the next few higher harmonics typically have $\langle b_M \rangle$ between 0.002 and 0.02. Each dispersive section immediately downstream raises the microbunching approximately 10-fold for the de-

sired harmonic resonant in the following radiator. Figures 1 through 3 show the sensitivity of output power from the 4- and 1-nm radiators to various input parameters. By operating in the low gain regime and by optimizing the dispersion sections's strengths to a particular input power, P_{out} appears relatively insensitive to P_{in} . This insensitivity also applies in part to input noise fluctuations in amplitude (see the next section).

NOISE GROWTH

It has long been known that up-conversion to harmonic M of a signal containing phase noise will in general increase the noise level of the output power by a factor M^2 ; when considering output field amplitude or phase, the relevant scaling is M^1 . Previous studies of FEL harmonic cascades [6][7] have shown that similar scaling can apply in the *high-gain* limit for amplitude noise (*i.e.* a time-varying \tilde{E} in Eq.1) although the latter reference has pointed out that the scaling is much weaker than M^2 in the high power, low-gain limit, where $\partial \log \langle b \rangle / \partial \log I \ll 1$.

With the exception of temporal slippage effects, it appears virtually impossible to escape the power law dependency upon M . Slippage results in a given electron slice interacting with a temporal radiation region $\tau_{slip} = (L_w/\lambda_w) \times \lambda_s/c$ which helps filter out the highest temporal frequency components from $d\phi/dt$. Here ϕ refers to the slowly varying phase in the eikonal approximation:

$$E(\vec{x}, t) \equiv \tilde{E}(\vec{x}, t) \times \exp[i(k_0 z - \omega_0 t + \phi(\vec{x}, t))] \quad (1)$$

Figure 4 shows the evolution of the phase noise level in a series of GINGER runs for which the initial 240-nm input laser signal had either broad-band electric field phase or amplitude noise at a level equivalent to 22 mrad rms per 240-nm wavelength superimposed upon a constant base signal. The output phase noise level (after removal of $\langle d\phi/dt \rangle$ which corresponds to a simple frequency offset) is plotted at the end of each radiator stage. For the 48-nm stage (*i.e.* $M = 5$), we show a second point which corresponds to the phase noise level near the beginning of the radiator; the decrease in noise level between the beginning and end of the 48-nm radiator illustrates the filtering effects of slippage.

At least three conclusions can be drawn from this figure (and close inspection of the actual $d\phi/dt$ curves):

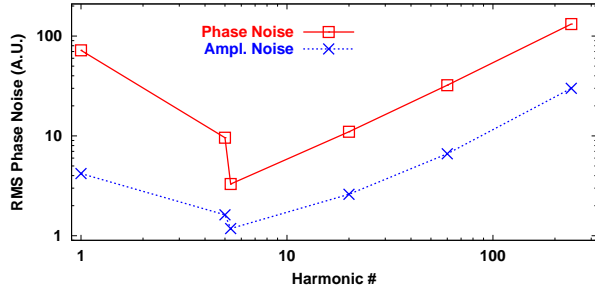


Figure 4: Residual rms phase noise $d\phi/dt$ following removal of the mean value at various harmonic stages for a LUX cascade initiated with pure phase/amplitude noise on the external seed laser.

- (1) For the first two stages, slippage acts as a low-pass filter and suppresses overall noise growth.
- (2) Eventually, phase noise components with small frequency offsets from ω_0 (*i.e.* with longitudinal scale lengths $\geq c\tau_{slip} \gg \lambda_0$) dominate and together with their M^1 growth scaling. The slope on the log-log plot in Fig. 4 for $M \geq 10$ is ≈ 1.0 as expected.
- (3) For our low-gain, high input power design, broad-band noise distributed purely in amplitude is much less important than that distributed purely in phase. In the initial cascade stages, amplitude noise partially converts to phase noise which then becomes dominant and with the expected power law scaling in the later stages.

We also examined the evolution of shot noise in the harmonic cascade. Due to the “fresh-beam” design and to slippage effects in the first two stages, the noise level remains small and is only of order 10 kW in the final 1-nm stage, less than one-thousandth the coherent output signal. Consequently, despite the $240\times$ increase in harmonic number, noise growth in this design may not significantly degrade output coherence down to wavelengths as short as 1 nm.

SHORT PULSE EVOLUTION

Some user applications may require output radiation pulse durations much shorter than the nominal ≈ 200 fs adopted in our sample design. For a *high gain* FEL cascade initiated with a Gaussian temporal profile, Saldin *et al.* [7] have predicted that the rms radiation pulse duration will tend to shrink by a factor \sqrt{M} from one stage to the next. However, as shown in Fig. 1, our high power, low gain design is less sensitive to input power variations and one expects less shrinkage. Moreover, in the extreme limit where the radiation pulse duration is quite short, one expects that slippage effects will place a lower limit on the output pulse duration from each stage. To study these phenomena, we initiated a LUX cascade with a Gaussian pulse with $\sigma_t = 5$ fs (11.2-fs FWHM) and examined the downstream $P(t)$. The GINGER simulations were done in full time-dependent mode and included shot noise effects. In

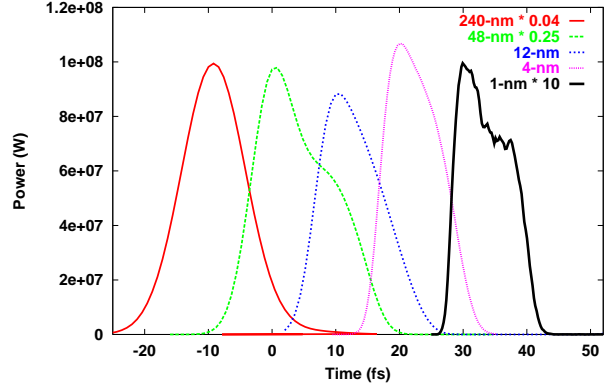


Figure 5: Predicted $P(t)$ profiles at different stages for a LUX cascade initiated with a Gaussian profile pulse with a 5-fs RMS duration. Each curve has been scaled by the indicated factor to fit on the plot.

order to obtain sufficient energy modulation in the first stage, the peak input power was increased to 2.5 GW from the nominal time-steady value of 1.0 GW. Figure 5 shows the output power profiles from each radiator stage. The FWHM temporal duration first increases to ≈ 15 fs at 48 nm, presumably because $\tau_{slip} = 24$ fs, but then shrinks back to a nearly constant ≈ 11 fs in the next 3 stages, in strong contrast to the scaling observed in [7]. Since the slippage is less than 3 fs in the 4- and 1-nm stages, the lack of additional pulse shrinkage must be due to high power effects. Some noise modulation appears on the 1-nm output $P(t)$ but it remains nearly completely temporally coherent.

SUMMARY

Our preliminary simulation results show that a XUV/soft x-ray FEL built upon the principle of a harmonic cascade will greatly enhance the proposed LBL LUX facility by providing coherent radiation in the ≤ 1 keV energy range. Future studies, which will include additional realistic effects such as undulator errors, electron beam transport optics, *etc.*, can help further determine the reality of the promise of a multi-stage harmonic cascade for LUX.

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